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AN INVESTIGATION OF SOLID PROPELLANT COMBUSTION IN STANDARD AND HIGH ACCELERATION ENVIRONMENTS

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Nonmetallized double-base and composite propellant, metallized composite propellant, and ammonium perchlorate (AP)/binder sandwich combustion were studied in standard and high acceleration environments. Experimental techniques used were high speed motion pictures, two-color schlieren, laser schlieren, and centrifuge mounted combustion bombs. It was found for double-base propellant that the temperature increased continuously from the surface into the visible flame.

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Acceleration induced burning rate augmentation occurred and resulted in elimination of the visible flame. Acceleration apparently modified the surface or subsurface zones. AP/binder sandwich combustion was also found to be acceleration sensitive with binder flow-AP interactions proposed as the mechanism. Composite propellants burned with local diffusion flames to pressures as low as 100 psi. A comparison is made between AP/binder sandwich combustion and propellant combustion.

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INTRODUCTION

The burning rate acceleration sensitivity of solid propellants has received considerable attention in the past ten years. A brief summary of the findings and a reference list has been presented by Netzer and Northam (1). Most of this work has been concerned with metallized composite propellants. For these propellants, acceleration induced retention of metallic agglomerates on the burning surface causes surface pitting. This is normally the dominant mechanism for burning rate acceleration sensitivity. Nonmetallized composite propellants have received less attention. Analytical models (1) have been proposed that assume either that acceleration affects the gas phase or that it affects the AP crystals which have been freed from the surface by preferential interfacial reactions between the AP and binder. However, the basic assumptions used in both models have not been verified experimentally. In fact, experimental evidence appears to invalidate the models. Northam (2) has also reported that solid impurities in the propellant may accumulate on the surface, resulting in surface pitting and increased burning rate. It was proposed by Cowles and Netzer (3) that the burning rate acceleration sensitivity of nonmetallized composite propellants is due to the interaction of the binder melt with the AP deflagration. Recently, Brown, et al (4) added credibility to this proposed mechanism based upon measured acceleration induced burning rate increases in AP/binder sandwich combustion in which binder flow onto the AP was observed. In that study only one binder (PBAA) was used. Additional investigations with other binder systems are required to further verify their initial findings.

Very little work has been done which provides information pertaining to the mechanism(s) responsible for the burning rate acceleration sensitivity of double-base propellants. Bulman and Netzer (5) found that in an acceleration environment lead and copper additives result in metallic "flooding" of the burning surface. This "flooding" resulted in a decrease in the propellant burning rate. Aluminum additives tended to increase the burning rate much as they do for composite propellants burned in an acceleration environment. However, Northam (2) found that small amounts of lead stearate additive can cause burning rate increases by surface pitting. Additional work is required with nonmetallized double-base propellants in order to determine the mechanism(s) responsible for burning rate acceleration sensitivity.

To date, the most promising model for composite propellant combustion appears to be that proposed by Beckstead, Derr and Price (6). However, it is difficult to verify this multiple flame model by direct experimental observation. Therefore, most recent work conducted to better understand composite propellant combustion mechanisms has been done with two-dimensional propellant sandwiches and wafers of ammonium perchlorate (4, 7-17). Sandwich combustion has provided a convenient method for studying AP-binder interactions but the applicability of the results to actual composite propellant combustion remains questionable. This is especially true with regard to flame characteristics where local mixture ratio and surface configuration may have dominant affects. Most of the above referenced research used high speed motion picture photography and scanning electron microscope examination of quenched samples. The results of the schlieren investigations by Brown, et al (4) and

Murphy and Netzer (15) appear to agree with the combustion behavior postulated by the above studies.

Schlieren studies of nonmetallized composite propellant combustion (4, 15, 18) have been limited to low pressures due to luminosity and smoke obscuration. Schlieren within the visible flame was not obtained in the sandwich studies (4,15) and to date the quality of direct observations of the surface behavior of nonmetallized propellants during combustion have been poor.

In order to obtain the required data for verification of proposed models, schlieren studies and direct observation of surface behavior during combustion are required. One possible means for obtaining these data is to use laser schlieren and monochromatic photography in which all visible light can be effectively filtered. However, the use of laser light for these purposes presents some unique problems.

The investigation presented herein was directed at; 1) determination of the mechanisms responsible for the burning rate acceleration sensitivity of nonmetallized composite and double-base propellants, 2) direct observation of composite propellant combustion in order to better determine the similarities and differences with AP/binder sandwich deflagration.

II. METHOD OF INVESTIGATION

This investigation consisted of several major studies, nonmetallized double-base propellant combustion in standard and high acceleration environments, AP/binder sandwich combustion in standard and high acceleration environments, composite propellant combustion, and the application of laser schlieren to solid propellant combustion research.

Double-Base Propellants

High speed motion pictures were taken of the double-base propellant combustion in a nitrogen purged combustion bomb. A film consisted of color schlieren with alternating normal light frames. These films were used to determine the flame position and structure, and the qualitiative behavior of the vertical and horizontal temperature profiles as a function of pressure (500 and 800 psia).

The static burning rate (zero g) was determined from a pressure-time trace in a combustion bomb attached to a high acceleration centrifuge. The pressure-time trace not only showed the burn time but also any fluctuations in pressure caused by instabilities in burning. Strand length of one and two inches were investigated and compared to burn data received from the Naval Ordnance Station (19). Most of the strands employed had a cross section of three-sixteenths by one-half inch. The pressure for both strand lengths were varied from 100 to 1250 psia. A somewhat less accurate static burning rate was also calculated from the high speed motion picture photography obtained with the combustion bomb and the optical centrifuge.

The burning rate augmentation was calculated from the high acceleration centrifuge data for two-inch strands with the same cross section as above. At pressures of 500 and 1000 psia, the acceleration was varied from zero to 1000 g's directed normal and into the burning

surface. Additional runs at negative 1000 g's (normal and out of the burning surface) were run at 1000 psia.

An additional optical study was performed using a high speed motion picture camera (3000 PPS) to observe the burning surface of the propellant and the flame position and behavior in acceleration environments. Because the combustion bomb on the optical centrifuge was small, the double-base strands were one-half inch in length with a cross section of three-sixteenths by one-quarter inch.

AP/Binder Sandwich Combustion

The AP/binder sandwiches were visually studied under accelerations of zero and 100 g's at a pressure of 400 psia. An optical centrifuge equipped with a high speed motion picture camera was used to record the surface behavior during combustion. The sandwiches were made with pressed polycrystalline ultra high purity ammonium perchlorate and two different binders, PU and HTPB. To determine the effect of the binder thickness on the burning rates, the sandwiches were constructed with two different thicknesses, 25 and 100 microns. The sandwiches were one-half inch high with a cross section of three-sixteenths by one-tenth inch. Burning rates under static and acceleration environments, and AP/binder interactions were determined from the films.

Composite Propellants

Aluminized and nonmetallized composite propellants were studied in the schlieren equipped combustion bomb. To facilitate observation of combustion behavior, 420 micron unimodal AP propellants were employed. Pressure was varied from atmospheric to 500 psi and high

speed motion pictures were taken with alternating frames of color schlieren and normal photography. The films were examined for flame structure and surface phenomena as a function of pressure to be compared with AP/binder sandwich deflagration.

Laser Applications to Solid Propellant Combustion Research

The investigation consisted of the development of a laser schlieren system to study the gas phase above the deflagrating surface.

Propellant sandwiches were constructed using ultra-high purity ammonium perchlorate as the oxidizer and polybutadiene acrylic acid (PBAA) as the binder. Binder thicknesses of 25 to 125 microns were used in the investigation.

The laser schlieren study was conducted using a nitrogen purged combustion bomb operated at 500 and 800 psig. A high speed motion picture was used to record the schlieren data. Each film was then examined to determine the obtainable schlieren quality.

III. EXPERIMENTAL APPARATUS AND PROCEDURES

Propellant Specifications

The constituents of the double base and composite propellants and the AP and binder specifications are presented in Table I. The double base propellant was supplied by the Naval Ordnance Station, Indian Head, Maryland, and the composite propellants were produced by the Naval Weapons Center, China Lake, California. Ammonium perchlorate was provided by the Kerr-McGee Corporation and binder ingredients were provided by the Thiokol Chemical Corporation, Huntsville, Alabama.

High Acceleration Centrifuge

The high acceleration centrifuge (20) has a nominal diameter of 76 inches. Propellants were burned in a nitrogen atmosphere to pressures of 1250 psia and accelerations to 1000 g's. The 115 cubic inch bomb was vented to surge tanks with a total volume of 1450 cubic inches. A pressure-time trace of the burn was produced on a Honeywell Visicorder model 1508.

The strands were rigidly inhibited on all sides and the base with Selectron 5119 resin and "Garox" curing agent.

A detailed description of the high acceleration centrifuge and the associated procedures have been presented in references 20 and 21.

Optical Centrifuge

The centrifuge was equipped with a Hycam model K1001, 16mm high speed motion picture camera mounted above a 24-inch diameter rotating table. The nitrogen purged bomb was capable of operating to 800 psia and 110 g's with the associated equipment installed. The nonmetallized

propellant required the use of a General Electric Marc 300/16 projection lamp as a light source. A timing mark was produced on the film edge by a Red Lake Laboratories Millimite TLG-4 timing oscillator. The camera was operated at 3000 pictures per second.

The optical centrifuge was originally designed by the United Technology Center and has been discussed in references 21, 22, and 23.

Combustion Bomb and Schlieren

The schlieren was produced with a red-blue matrix and was used to obtain both vertical and horizontal density gradients. A light source chopper was placed between the bomb and the schlieren source to create alternating frames of real light photography. A film speed of 7500 pictures per second was used. The bomb had a maximum operating pressure of 1000 psia. A Hycam model K2004E-115 high speed motion picture camera and a Red Lake Laboratories timing oscillator recorded the burn.

The combustion bomb has been detailed in reference 22. Modifications to the bomb and the color schlieren are discussed in reference 15.

Laser Schlieren System

The basic schlieren system, combustion bomb apparatus, and high speed camera set-up are discussed above. Experimental apparatus utilized during the investigation are shown in Table II. A 2-watt per line argon laser was substituted for the mercury arc source. A diverging lens was used to expand the laser beam. The expanded beam was then passed through a focusing lens which focused the laser beam at the focal point of the first schlieren lens, thus yielding an expanded parallel beam of light through the test section. A light source chooper (15) was

also located at this point (see Figures 1 & 2).

A neutral density wedge filter and a conventional knife edge were used in an attempt to obtain schlieren information using the argon laser as the light source. Both objects were mounted on an adjustable platform with micrometer adjustments available in the horizontal and transverse directions. A laser line filter was located between the knife-edge and the 610-millimeter focusing lens. This lens focused the sandwich burner image on the film plane and gave a magnification of 0.8.

AP Wafer and Sandwich Fabrication

The polycrystalline AP wafers were molded at a pressure of 30,000 psi for 20 minutes. The binder curing processes are given in Table I.

The fabrication techniques have been presented in references 15 and 22. Propellant and sandwich dimensions were determined with a Gaertner Scientific Corporation measuring microscope.

IV. RESULTS AND DISCUSSION

All photographs are reproduced in black and white from color prints. The color prints along with two edited films, one on double-base propellant and the other on sandwich deflagration, are available on loan from Associate Professor D. W. Netzer, Naval Postgraduate School, Monterey, California.

Double-Base Propellant

The study of the horizontal density profile using the vertical knife edge schlieren, figures 3 and 5, showed alternating colors in the gases above the deflagrating surface. This apparently results from distinct burning sites on the propellant surface. The size of these sites was found to be independent of pressure (at 500 and 800 psia). Site width varied from 150 to 200 microns. The sites moved very slightly in their horizontal position and remained well defined for periods of 25 to 50 milliseconds. This was similar to observations of AP deflagration by Murphy and Netzer (15).

The vertical density profile, figures 4 and 6, showed the density continuously decreasing from the surface into the visible flame. Assuming that the density variation is predominantly determined by temperature variations, the films indicate a continuously increasing temperature from the surface into the visible flame. A quantitative temperature gradient cannot be determined from the film but the uniformity of the red color indicates the lack of any significant temperature plateau in the "dark zone". This result is different from many previous studies (24) in which the "dark zone" is reported to have a constant temperature region for double-base propellants containing ballistic modifiers.

Reference 24 presents an approximate expression for the height of the "dark zone" (distance from the surface to the visible flame) as $10^7/p^3$ inches, with p in psi. The flame heights calculated from the films at 500 and 800 psia agreed closely with this expression.

The static burning rates determined from the two-inch strand length had less variation than the shorter one-inch strands and therefore, the longer strands were used throughout the study. The pressures in the high acceleration centrifuge were varied from 100 to 1250 psia. There were no combustion instabilities observed in the pressure-time traces taken under static conditions. These burning rate data were repeatable to within 5 percent which also indicated a stable burning process. The burning rate data supplied by the Naval Ordnance Station (19) included pressures from 500 to 4000 psia. Figure 9 compares the burning rate data at pressures that were common to both facilities. The two lines in Figure 9 have nearly equal slopes, with the Naval Ordnance Station data exhibiting slightly higher burning rates. This was due in part to the different temperatures at which the propellant was burned but may also have resulted from different strand preparation and testing techniques. Tests with a larger cross section strand (one-half by one-half inch) showed that the burning rate was not affected by strand cross section. Therefore, the smaller cross section was used for all subsequent tests.

The static burning rates obtained from the combustion bomb and the optical centrifuge were within a maximum difference of 30 percent from those determined in the high acceleration centrifuge. The average difference was less than 20 percent. These differences were probably due to the transient effects of ignition and the relatively small size samples required in the combustion bomb and the optical centrifuge. In addition,

the strands used in the combustion bomb and the optical centrifuge were not inhibited. Those used in the high acceleration centrifuge were rigidly inhibited.

Burning rate augmentation was observed at high accelerations for the nonmetallized double-base propellant. Figures 10 (a) and 10 (b) show the augmentation as a function of acceleration at 500 and 1000 psia, respectively. The static burning rates at 500 and 1000 psia were 0.271 and 0.452 inches per second respectively. Instabilities in combustion at high accelerations were indicated by observed oscillations in the pressure-time trace and may be the cause for the data scatter shown in Figure 10. The burning was more stable at the lower accelerations and the higher pressure (1000 psia). Tests at negative 1000 g's showed no augmentation and indicated the same stable combustion exhibited under static conditions.

The optical centrifuge films showed the yellow visible flame under static conditions (figure 7). At accelerations of 100 g's the visible flame was eliminated (figure 8).

Calculations of the acceleration induced pressure increase at the bottom of a 100 micron liquid layer on a propellant surface showed it to be insignificant at 100 g's. The gas phase would be affected even less.

The above results indicate that the primary mechanism for burning rate augmentation is most likely contained in a two-phase region within the burning surface. In this region, density differences are more pronounced and could be more significantly affected by acceleration fields. This region is referred to as the subsurface zone. The

subsurface zone is just below the propellant surface and is thought to be comprised of gas and liquid in which an exothermic reaction occurs (25). The obvious effects of the acceleration environment were the elimination of the visible flame and the inducement of burning instabilities. The former apparently occurred as a result of changes in the products of combustion.

One possible mechanism for the observed augmentation is that the acceleration causes a change in the interaction of the gas and liquid phases, thereby increasing the heterogeneous reaction rates. Coupled with this is the possibility that the acceleration induced changes in the combustion products may increase the radiation to the surface in the ultraviolet spectrum. The double-base propellant contained no opacifying agents such as carbon black.

Sandwich Deflagration

Tables III and IV summarize the results obtained with sandwich burners. Figures 11 through 16 are photographs which were typical of the burns obtained for the various binders, binder thicknesses and accelerations.

As shown in Table III and IV, the static burning rates were sensitive to binder thickness. PU burned with approximately the same rates for both binder thicknesses, while the 0.004 inch HTPB burned faster than the 0.001 inch HTPB.

Under static conditions, sandwiches made with 0.001 thick binders of PU and HTPB showed similar flame characteristics. The flame width at its base was not much larger than the binder width. This fact, along with the small flame size, indicated that not much binder flow occurred.

The 0.004 inch binders apparently had more binder flow onto the surface of the AP, as evidenced by an increase in the base width of the flame.

At accelerations of 100 g's, the 0.001 HTPB would not sustain combustion. The strands would not ignite, or would burn approximately 0.1 inch and extinguish. Sandwiches made with 0.004 inch thick HTPB binder exhibited burning rate augmentation at 100 g's but self-extinguished approximately half way through the burn. The quench appeared to result from excessive binder flow. Sandwiches made with the two PU binder thicknesses also exhibited increased burning rates at 100 g's. The flames in all cases were more intense than the corresponding burns under static conditions. The film of the sandwich with the 0.004 inch thick PU binder showed large pools of binder flowing onto the surface of the AP. Some of these pools would not ignite and eventually dropped off the surface. The ones that did ignite produced other burning sites separate from the primary AP/binder diffusion flame.

The apparent mechanism for augmentation is the binder flow onto the AP which caused a larger flame. This result is in agreement with the earlier work of Brown, et al (4). For HTPB, the binder flow was critical. At 400 psia, AP crystals with no binder would support combustion but this pressure is close to the low pressure deflagration limit of AP. The low pressure together with the nitrogen purge system in the optical centrifuge, appeared to cause AP/HTPB sandwich combustion to be very sensitive to binder flow.

For viscous binders (HTPB, etc.) excessive binder flow appears to quench the combustion whereas small amounts of binder flow enhance the burning rate. For binders which readily flow onto the AP in a thin film (PU), binder flow apparently enhances the burning rate.

Composite Propellants

Multiple tests were conducted at pressures of atmospheric, 100 psig, and 500 psig for both the metallized (N-8) and nonmetallized (N-3) composite propellants (see Table I(c)) in a nitrogen purged combustion bomb. Propellants were burned in strand configuration. Strand height varied between 0.25 in. and 0.375 in. and strand width (as viewed in figures) varied between 0.18 in. and 0.23 inc. Strand thicknesses employed are discussed below.

Nonmetallized Propellant N-3

While attempting to minimize the intensity of the visible yellow light by using very thin propellant strands, other problems were encountered. The strands had very little longitudinal stiffness. In addition when the thickness of the N-3 propellant strand was less than .034 inches, ignition attempts were unsuccessful at all pressures. These propellant "mini-strands" were apparently quenched by heat loss from the surface to the purge medium and/or by ignition induced binder flow, and/or by surface starvation of AP. Examination of the strands after unsuccessful ignition showed evidence that AP decomposition had occurred. Black charred pockets were evident along the top surface. Examination of these pockets with a microscope revealed a glazed-over surface lining the pocket, presumably formed by cooled binder melt. Seldom were any AP crystals observed protruding from the top surface of these strands. In addition, ignition attempts with these "mini-strands" of N-3 propellant at 500 psig were totally unsuccessful, even at thicknesses of .040 inches. Experiments with conventional strand dimensions were not practical in the current experimental apparatus

because of the schlieren light being overpowered by the yellow flame light.

Several strand shapes were tested in an attempt to obtain strands which would burn with a thickness less than .034 inches. Dumbbell and "T" shapes were used. Various wedge shapes were also tried. Although significantly thinner strand portions were successfully ignited and burned, no useable data was obtained because of uneven surface burning and excessive luminosity above the thicker portions of the strands.

Figure 17 contains a time sequence of propellant N-3 at 100 psig. Even with the thin strands, schlieren information was minimal with the 1000 watt light source. It is apparent from these photographs that surface regression was non-uniform. In figure 17(a), individual flames are seen around and above each of the AP crystals. In figure 17(b) the deflagration on the right half of the strand has ceased and the binder appears to be flowing from right to left. It is believed this quenching is caused by the flow of binder melt over the AP crystals.

Propellant N-3 typically displayed very irregular burning. As a single AP crystal first became exposed on the surface it would burn with several individual flamelets around its periphery. As the binder was consumed and more of the AP surface was exposed, the flamelets merged to form a closed flame over the oxidizer crystal. This is opposite to the behavior observed in the AP binder sandwich experiments. Binder melt appeared to be appreciable, with occasional evidence of distinct flow over some areas of the surface. The flames were laminar, in agreement with AP/binder sandwich flames.

Thus, at low pressures, there are some distinct differences between AP/binder sandwich deflagration and normal propellant combustion. The excess oxidizer present in sandwich burners apparently causes the visible diffusion flames to close above the binder whereas in propellant combustion the flame is observed to close above the oxidizer crystal. The closed diffusion flame above the oxidizer particle is in agreement with the model proposed by Beckstead, Derr and Price (6). However, the transition to a premixed flame at low pressures, proposed in the model, apparently occurs below 100 psi.

Surface irregularities caused by the varying AP size and the basic inhomogeneity of the propellant also appear to cause more binder melt interaction with the AP in propellant combustion than in sandwich deflagration. The binder flow differences may become even more significant at higher pressures where the AP crystals are recessed below the surface.

Metallized Propellant N-8

The metallized N-8 propellant "mini-strands" ignited and burned much more readily than nonmetallized N-3 propellant. Strands with thicknesses of .012 inches were successfully ignited but the deflagration was very sporadic and uneven. A compromise between excessive luminosity and sporadic burning was found at a strand thickness of .021 inches for the N-8 propellant. The longitudinal stiffness problem was even more critical with this propellant. The improved burning qualities of the N-8 was attributed to the additional energy given off by the uniformly distributed burning aluminum particles.

The hot aluminum particles apparently attracted each other and they formed into agglomerates which grew in size until drag forces from the rising hot gas forced them off the deflagrating surface. As they detached, they tended to pull smaller hunks and particles with them in their wake. The schlieren was again difficult to evaluate because of the additional luminosity provided by the burning aluminum powder in the propellant. In general, agglomerates formed and left the surface in less time than the comsumption time for an AP crystal.

Figure 18 is a schlieren photograph of propellant N-8 taken at 500 psig. The surface is more nonuniform and the gases above the surface more turbulent than at 100 psig, but the various reaction sites on the strand surface can still be distinguished by the alternating red and blue patterns. A binder protrusion is present in the middle of the strand and a patch of binder melt is located in the right corner.

At 500 psig, the schlieren above the deflagrating surface of the composite propellants exhibits the same surface generated "turbulence" as that found in AP/binder data at this pressure. Also, the binder protrusion in Figure 18 is characteristic of sandwich deflagration at high pressures.

Figure 19 (a) and (b) show N-8 propellant combustion at 100 psig. Flame configuration is similar to the nonmetallized N-3 results which closed flames above the AP crystals. A glowing aluminum agglomerate is located to the left and the flames surrounding individual AP crystals are seen to the right.

There appears to be more flow of the binder melt on both propellants N-3 and N-8 than on AP/binder sandwiches. This observation again lends support to the proposal (Ref. 3.) that binder flow causes burning rate acceleration sensitivity in both nonmetallized and metallized composite propellants.

Laser Schlieren

This section will discuss problems generated by the laser light itself, and specific problems encountered while trying to adapt the use of laser light to a schlieren system.

Due to the inherent danger of eye damage using a laser light source of high power, safety goggles are a mandatory requirement. However, when goggles are employed it is impossible to see any schlieren or to make any fine adjustments in schlieren quality. As a first attempt to solve this problem, neutral density filters were used. However, even at low power the brilliance of the reflected image was too intense to allow thorough examination of the schlieren quality. This problem was further compounded when the 610 mm focusing lens and camera were put into the system. (See Fig. 1).

The solution to this problem was to use an orange viewing screen. The orange viewing screen made the 4880 wavelength light of the argon laser visible while wearing the safety goggles. This allowed simple determination of correct knife-edge position and examination of the schlieren quality.

A further problem encountered when using the argon laser as the schlieren light source was a "speckle" background effect that occurred on the high speed film (See Fig. 20). While this effect remained essentially constant throughout a data run, it made interpretation of schlieren data extremely difficult. The speckle pattern has been discussed in the literature (26) and techniques are available for minimizing this effect.

The main problem that occurs when laser light is used for schlieren observations is that the light does not obey the hypotheses of geometrical

optics (27). This is due to the parallel, monochromatic and long coherence length characteristics of laser light. Oppenheim, et al (27) have also pointed out that the undistorted images that occur at the foci of the schlieren system are extremely small, being on the order of the diffraction patterns caused by the confining apertures.

A conventional knife-edge was used to examine both burning propellant samples and a candle flame. When density variations were present in the test section, a pattern of closely spaced fringes occurred rather than a smooth transition from light to dark, which is normally characteristic of schlieren data. The turbulence that existed in ammonium perchlorate/binder sandwich combustion caused extensive fringe patterns and this combined with the "speckle" effect yielded little useful data. A candle flame showed a more characteristic schlieren pattern with little distortion due to fringe patterns. This is due primarily to the laminar flame associated with the burning candle (See Fig. 21).

Further, due to the long coherence length of the laser light source, the light tended to diffract around the sharp edges of the two-dimensional propellant sample. This effect, combined with the fringe patterns, made determination of the actual burning surfaces extremely difficult (See Fig. 22).

In both of the preceding pictures, the visible "flame light" has been eliminated. This would permit the observation of the density gradient in the visible flame if a smooth continuous schlieren could be obtained.

In an attempt to alleviate the diffraction pattern interference which occurred with the use of a conventional knife-edge, a neutral density linear wedge filter was placed in the system at the focal point of the second schlieren lens. In effect this allows the removal of the solid edge associated with the conventional knife-edge. The result was good schlieren data with only minor fringe pattern effects due to propellant surface imperfections and minor diffraction patterns resulting from the neutral wedge filter.

These results were obtained at extremely low power (below 0.25 watts) but at any power setting above this minimum value the concentrated beam destroyed the vacuum deposited metallic coating material of the wedge filter. The present laser had a minimum power of 0.35 watts when properly tuned to the 4880 wavelength.

A similar phenomena occurred when a standard reflective type neutral density filter was utilized at the focal point. With the beam located at the edge of the filter material, good schlieren data was obtained but the neutral density material was rapidly destroyed by the focused laser beam.

A possible solution to both of the above problems would be the use of a more heat resistant coating.

Oppenheim, et al (27) have discussed the problems of using laser light in schlieren systems. They used a linear neutral density wedge filter in conjunction with a continuous gas laser and obtained schlieren data of a free jet flame with limited fringe patterns. This work was done at sufficiently low power to avoid damage to the filter material.

For high power study, Oppenheim, et al used a prism of quartz which rotated the plane of polarization of the laser beam. The final direction of rotation was dependent on the thickness of the prism and therefore, on the position of the incident beam on the prism. A sheet of polaroid placed anywhere beyond the prism provided a variation of light transmission from complete transmission to extinction. The study was conducted using a pulsed ruby laser, and a clear detailed schlieren record was obtained without damage to the experimental apparatus and without any appreciable fringe patterns.

Another material which may be employed as a knife-edge is a wedge or prism made of an absorbing type neutral density material.

Both a quartz crystal and a neutral density prism are currently being employed at the Naval Postgraduate School.

A third recommendation for further study is the use of a piece of "photostress" material and a piece of polaroid. This method employs the use of a birefringent material similar in principle to the quartz crystal. While this method was briefly examined in this investigation, it was not studied extensively enough to determine its validity.

V. CONCLUSIONS

Double Base Propellant

(1) Distinct burning sites exist on the burning surface of nonmetallized double base propellant.

(2) Gas phase density was found to decrease continuously from the surface into the visible flame. Assuming that the density variation is predominantly determined by temperature variations, the temperature increases continuously from the surface into the visible flame.

(3) The flame position depends on pressure and can be approximately calculated using $10^7/p^3$ inches, with p in psi.

(4) High positive accelerations cause burning rate augmentation and instabilities and eliminate the visible flame. Negative accelerations do not cause burning rate augmentation or instabilities.

(5) Acceleration apparently affects the surface or subsurface zones by causing a different interaction between the liquid and gas phases. This may result in increased heterogeneous reaction rates and/or modification of the combustion products such that UV radiation to the surface is increased.

Sandwich Deflagration

(1) Increased binder thickness had no significant effect on burning rates of AP/PU sandwiches but increased the burning rate of AP/HTPB sandwiches.

(2) Binder flow occurs under static conditions.

(3) Burning rate augmentation occurs at high accelerations for AP(UHP)/binder sandwiches.

(4) The apparent augmentation mechanism is increased binder flow onto the AP (which causes larger visible flames).

(5) AP/HTPB sandwiches are very sensitive to binder flow and self extinguish at 400 psia and 100 g's.

Composite Propellants

(1) As an AP crystal is first exposed to the burning surface, small individual flamelets exist around its periphery. At low pressures, as the AP protrudes above the surface, the flamelets merge to form a closed diffusion flame over the AP. This is in agreement with the model of Beckstead, Derr and Price (6) but opposite to the results for AP/binder sandwich deflagration where the diffusion flames at low pressures close above the binder protrusion.

(2) Distinct diffusion flames exist above the AP crystals to pressures as low as 100 psi.

(3) Binder flow appears to occur more readily in propellant combustion than in AP/binder sandwich deflagration and causes local surface quenching.

(4) At 500 psi, propellant combustion yields the same surface generated "turbulence" as found in AP/binder sandwich deflagration.

(5) At 500 psi, binder protrusions above the surface occur in propellant combustion as in sandwich deflagration.

(6) More powerful ($>$1000 watt) arc-lamps or laser sources will be required for schlieren studies of propellant combustion at high pressures.

Laser Applications to Propellant Combustion

(1) The "speckle" effect is a major deterrent to obtaining high speed motion picture laser schlieren data.

(2) A conventional knife-edge cannot be used to examine highly turbulent gas phase phenomena because of the resulting severe fringe patterns.

(3) At a power setting above 0.25 watts, currently available reflective type linear neutral density wedge filters cannot be used as a "knife-edge".

(4) By utilizing a laser line filter, the "visible flame" can be removed from high-speed motion picture studies, permitting study of the density gradient in the flame front.

(5) The use of a quartz crystal and polaroid sheet are recommended for use as the "knife-edge" in future laser schlieren studies.

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TABLE I

PROPELLANT SPECIFICATIONS

(a) Double Base Propellant

Constituents	Per cent by Weight
Nitrocellulose	50.5
Nitroglycerin	46.8
2-nitrodiphenylamine	2.2
Di-n-propyl Adipate	0.4
Candelilla Wax	0.1

(b) Propellant Sandwiches

AP

Designation	Crystal Size*	Principal Impurities (wt per cent)
UHP	38.1% > 297μ	Sulfated Ash 0.01%
	81.9% > 211μ	
	99.6% > 104μ	

Binders

Type	Constituents	Per Cent by Weight	Cure**
HTPB	HTPB	93.7	168.0 hr at 60°C
	IPDI	6.3	
PU	Adiprene	72.0	120.0 hr at 48°C
	Castor Oil	27.9	
	1, 4 Butane Diol	0.1	

* Typical values from manufacturer data sheet
** First three hours in vacuum in excess of 28 in. Hg.

TABLE I (Cont'd)

PBAA	PBAA	84	96 hrs at 72°C
	EPON 828	16	

(c) Composite Propellants

Designation	Binder	Per cent Binder by Weight	AP size μ	Per cent AP by Weight	Aluminum size μ	Per cent Aluminum by Weight
N-3	PBAN	21	420-500	79	–	–
N-8	PBAN	18	420-500	67	44	15

TABLE II EXPERIMENTAL APPARATUS

Schlieren	Control Laser Model 902A Argon CW Ion Laser
Film	Kodak Ektachrome 7241 ASA 40
Laser Line Filter	Corion Instrument Corp. 100-4880-1 Filter
Camera	400 ft., 16mm Hycam Camera frame rate: 400-7500 shutter 1/2.5
Knife-edge	1. Conventional knife-edge 2. Optical Industries Rectangular Neutral Density Wedge Filter Range: 0.0-1.0
Schlieren focusing lens	610mm, f6

TABLE III

Summary of Data from AP (UHP)/PU Sandwich Tests

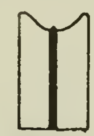
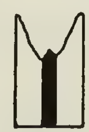
Pressure (psia)	Acceleration (g)	Average Burning Rate (in/sec)	Binder Thickness (in)	Burn Profile	Remarks
400	0	0.08	0.001		Small nonsteady flame at the AP/binder interface. Small amount of binder flow onto the AP.
400	0	0.09	0.004		Larger turbulent flame at the AP/binder interface. Small amount of binder flow onto the AP.
400	100	0.11	0.001		Small, but somewhat larger than at zero g, burning at the AP/binder interface. Small amount of binder flow onto the AP.
400	100	0.12	0.004		Larger flame than zero g burning with much binder flow onto AP. Pools of binder on the surface of the AP. Some ignited to produce secondary burning sites.

TABLE IV

Summary of Data from AP(UHP)/HTPB Sandwich Tests

Pressure (psia)	Acceleration (g)	Average Burning Rate (in/sec)	Binder Thickness (in)	Burn Profile	Remarks
400	0	0.08	0.001		Small, but closely spaced separate flames at the AP/binder interface. Very little binder flow onto the AP.
400	0	0.12	0.004		Large continuous flame burning with a larger width than the binder. Some binder flow observed.
400	100	-	0.001	-	No sustained combustion in five attempts.
400	100	0.15	0.004		Large continuous flame which was wider than the binder. Binder flowed on both sides until it finally quenched itself.

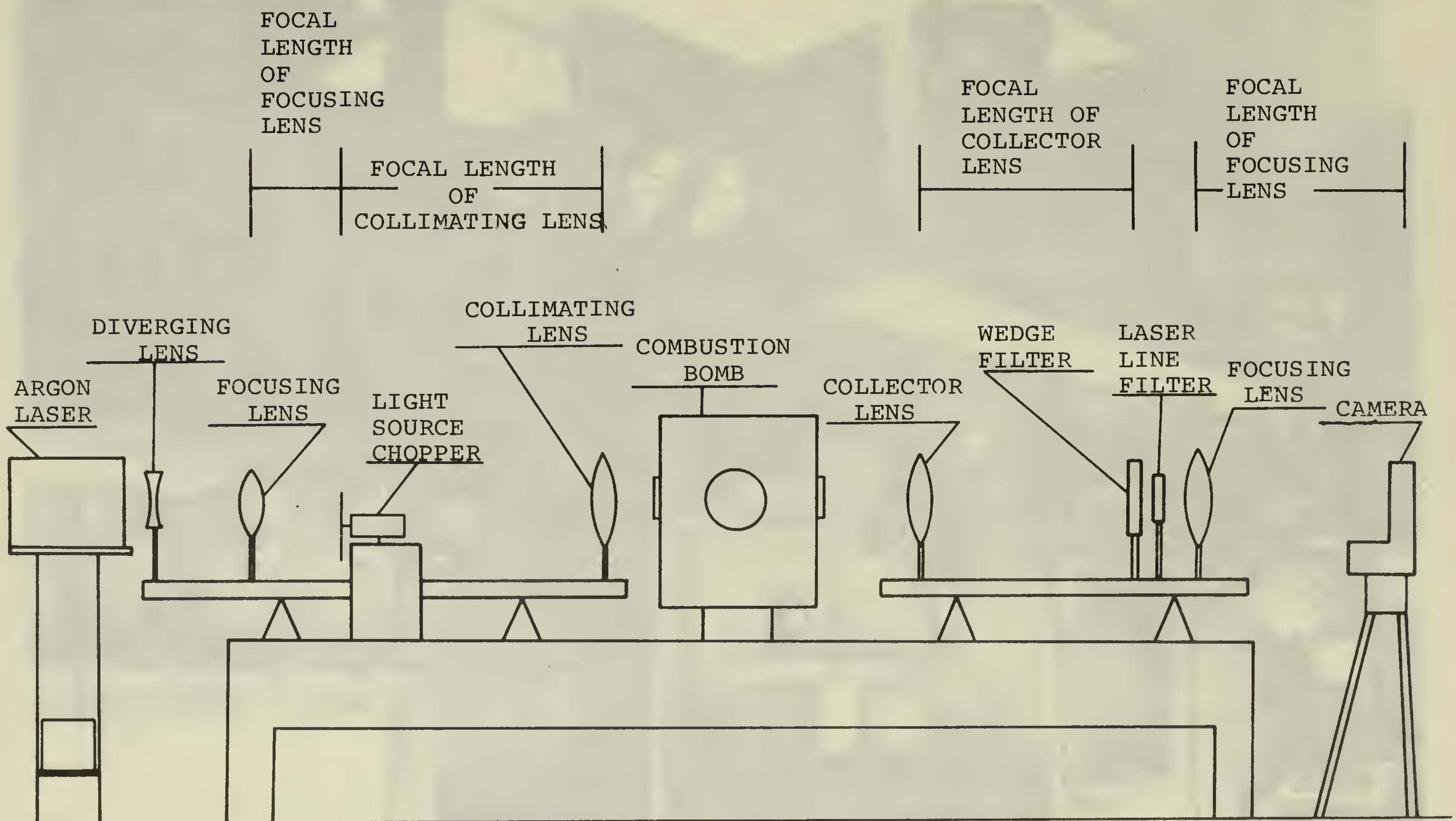


Figure 1. Schematic of Laser Schlieren

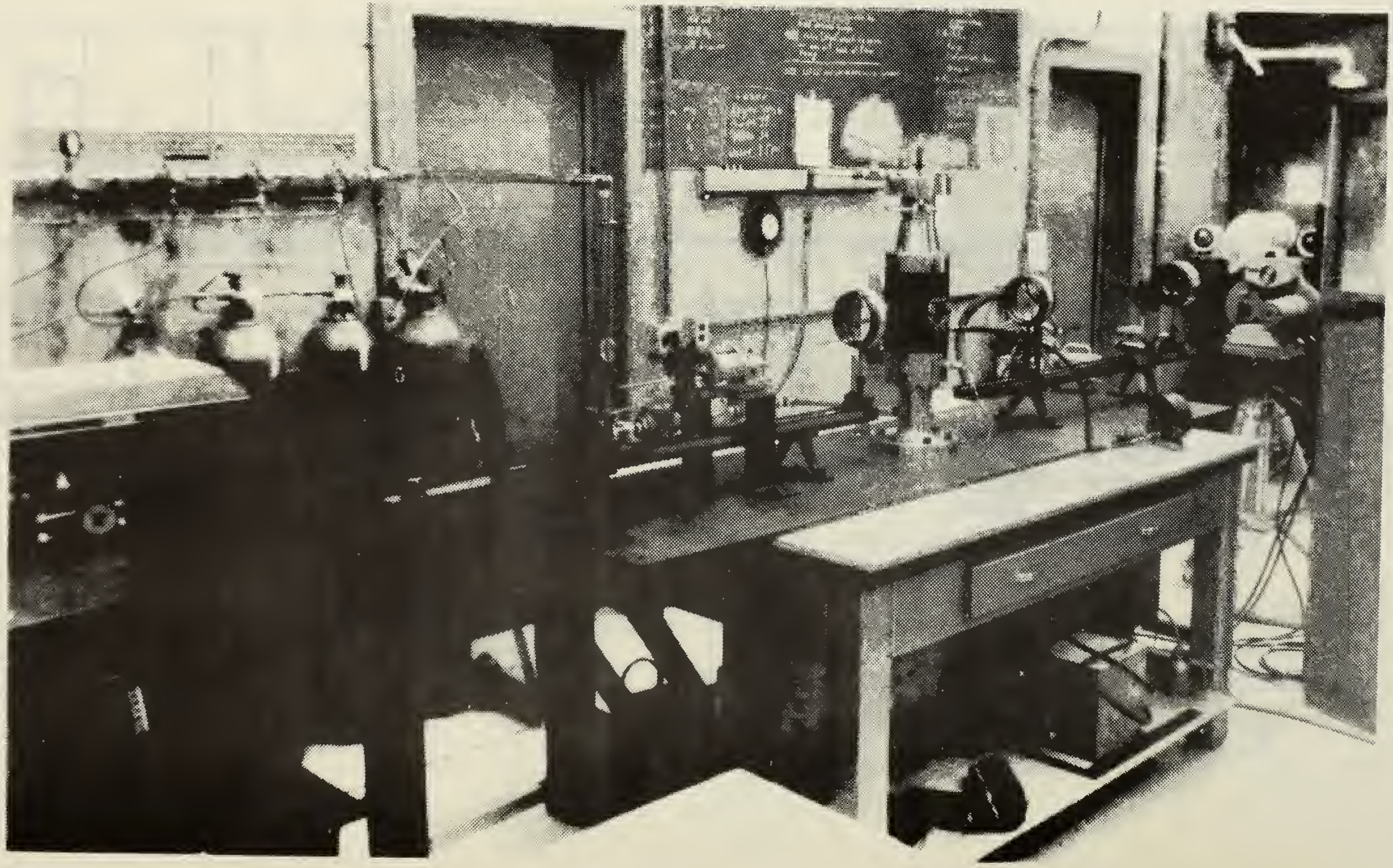
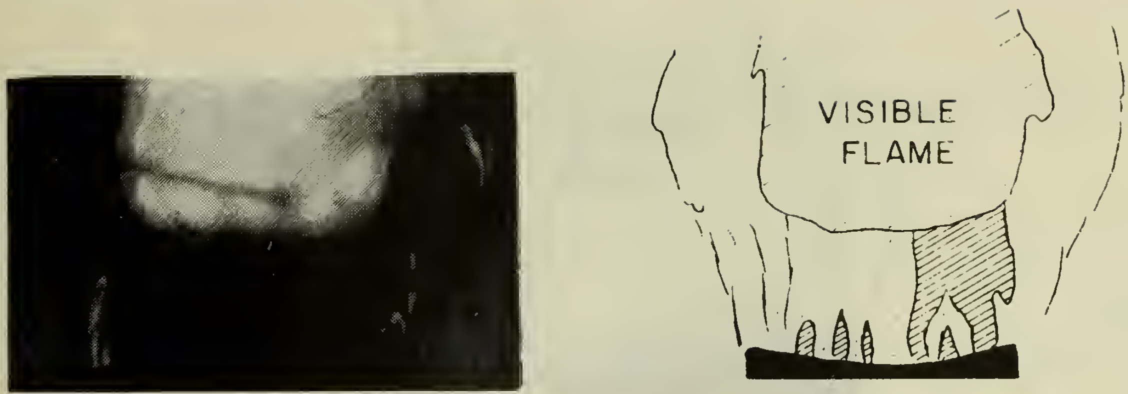


Figure 2. Photograph of Laser Schlieren Apparatus



(a) Black and White Reproduction (b) Schematic //// Red
⁚ Blue

Figure 3. Color Schlieren-Double-Base Propellant at 500 psia (horizontal density profile)

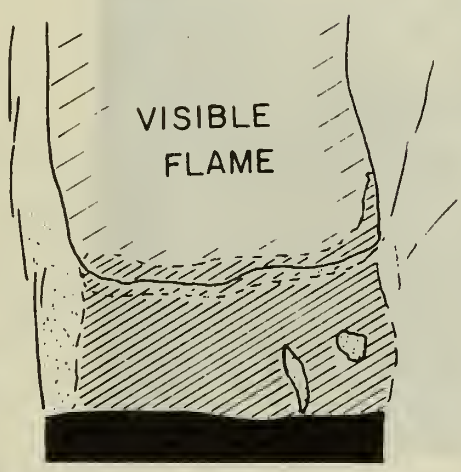


Figure 4. Schematic of Color Schlieren-Double-Base Propellant at 500 psia (vertical density profile): //// Red, ⁚ Blue.

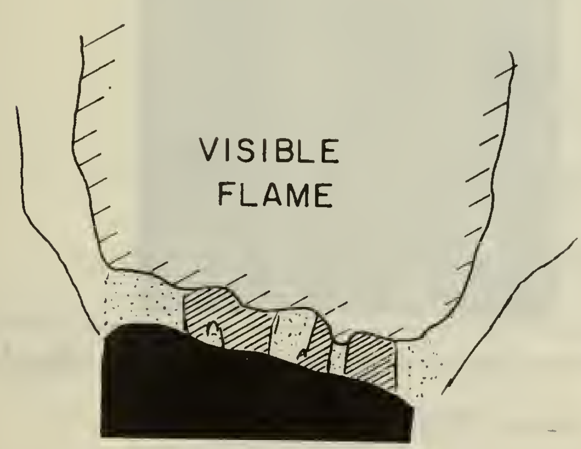


Figure 5. Schematic of Color Schlieren-Double-Base Propellant at 800 psia (horizontal density profile): //// Red, ⁚ Blue.

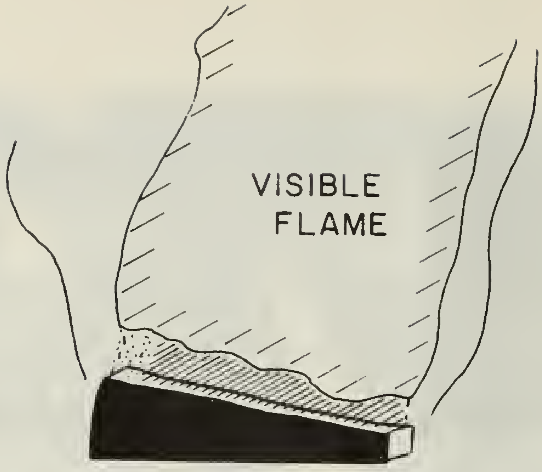


Figure 6. Schematic of Color Schlieren Double-Base Propellant at 800 psia (vertical density profile). //// Red, ⁘ Blue.

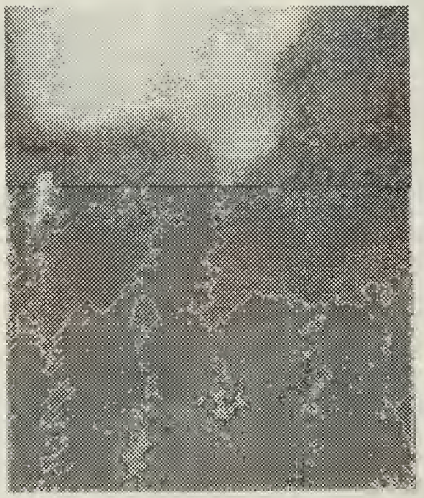


Figure 7. Double-Base Propellant Combustion at 0 g's, 400 psia

Figure 8. Double-Base Propellant Combustion at 100 g's, 400 psia

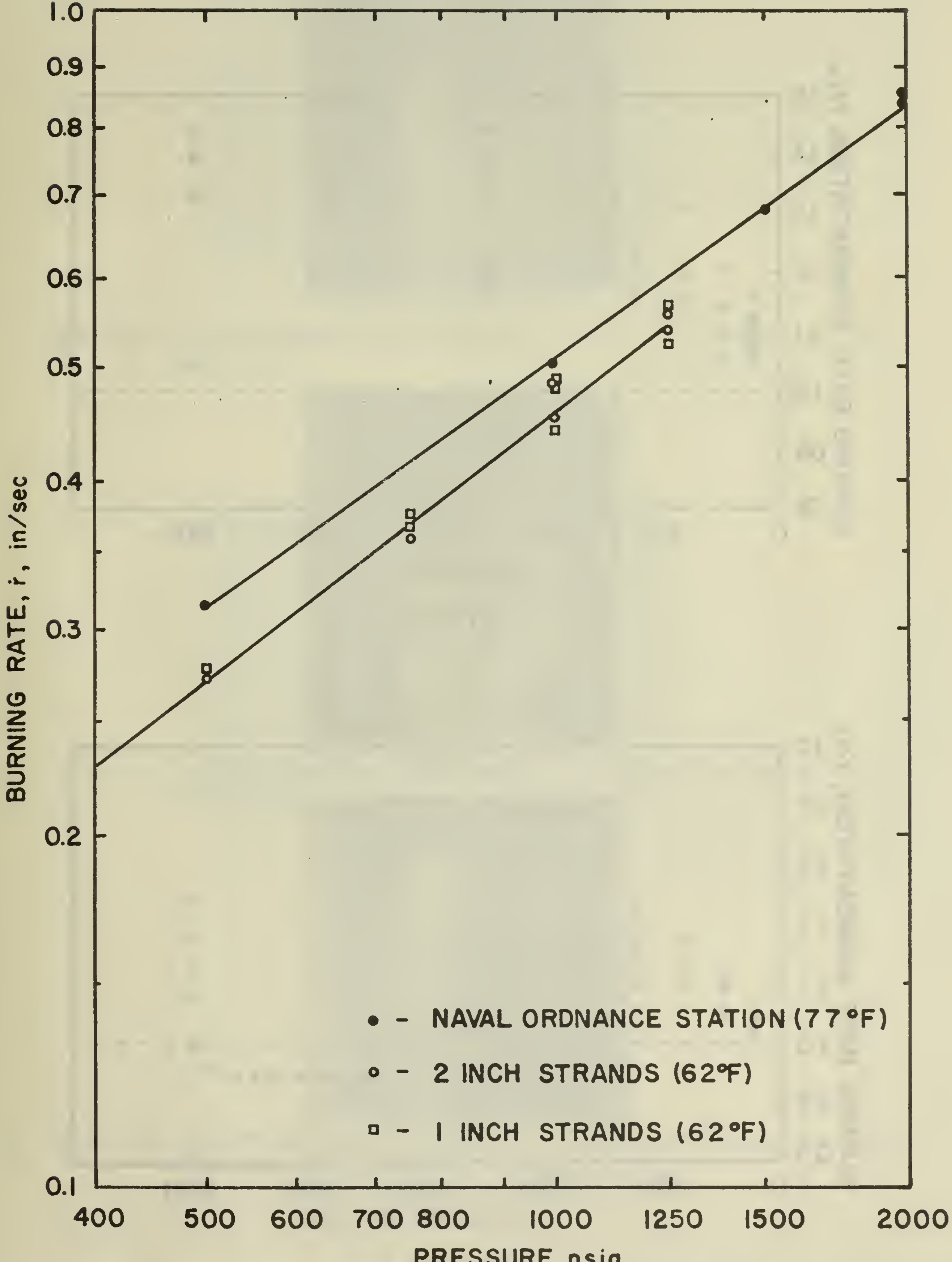


Figure 9. The Effect of Pressure on the Burning Rate of Nonmetallized Double Base Propellant.

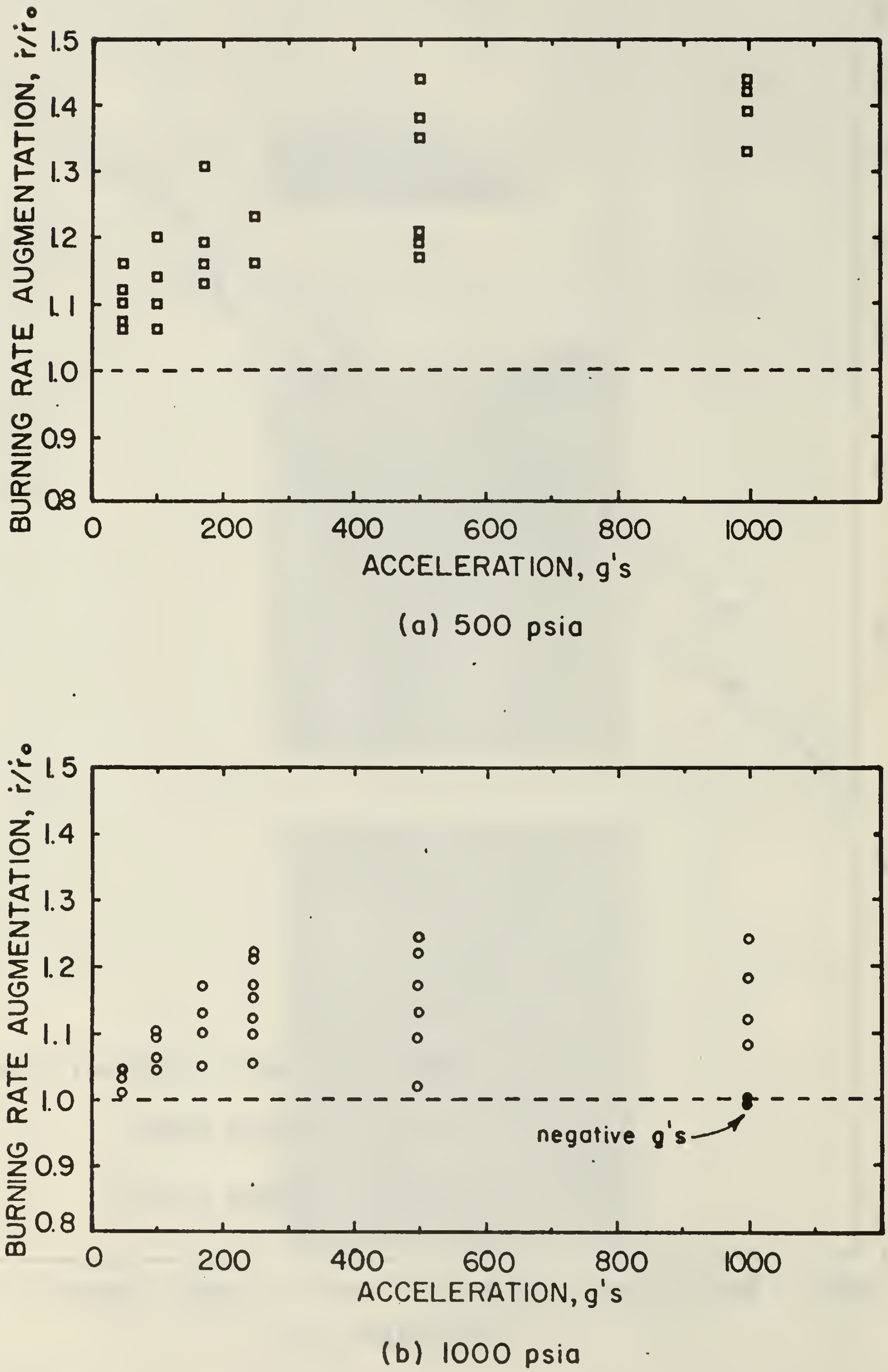


Figure 10. The Effect of Acceleration on the Burning Rate of Nonmetallized Double Base Propellant.

Figure 11. AP/PU Sandwich Combustion, 0.001 inch Binder at 0 g's, 400 psia

Figure 12. AP/PU Sandwich Combustion, 0.004 inch Binder at 0 g's, 400 psia

Figure 13. AP/PU Sandwich Combustion, 0.001 inch Binder at 100 g's, 400 psia

Figure 14. AP/PU Sandwich Combustion, 0.004 inch Binder at 100 g's, 400 psia

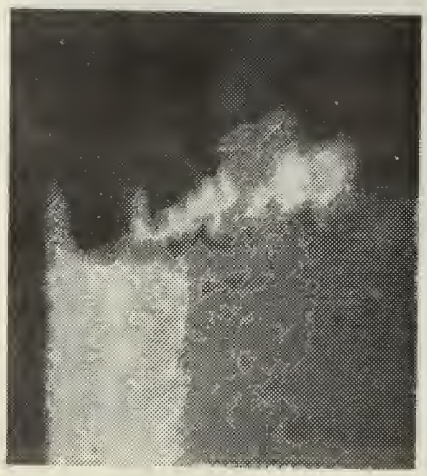
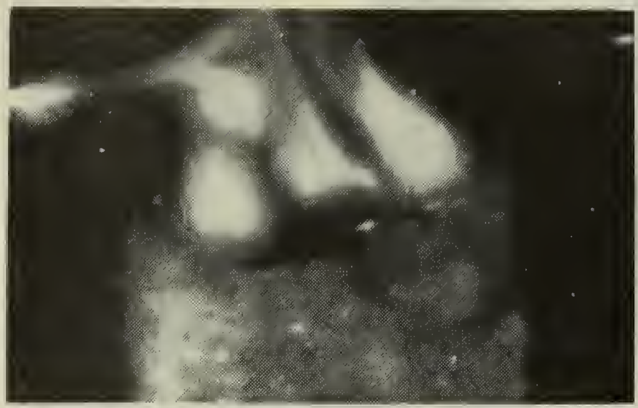
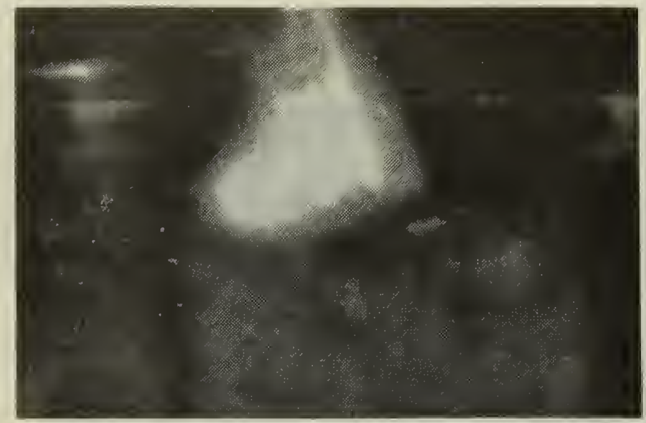


Figure 15. AP/HTPB Sandwich Combustion, 0.001 inch Binder at 0 g's, 400 psia

Figure 16. AP/HTPB Sandwich Combustion, 0.004 inch Binder at 0 g's, 400 psia

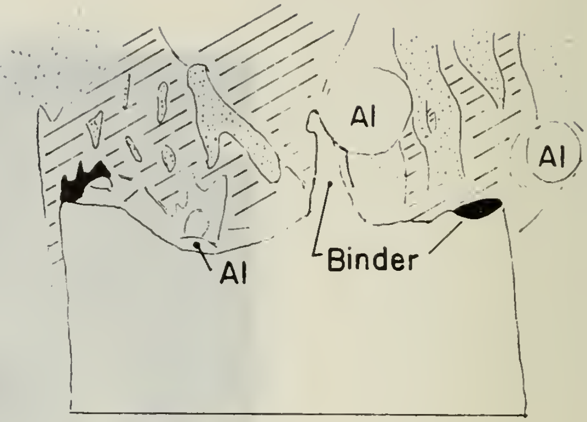


(a) time = to



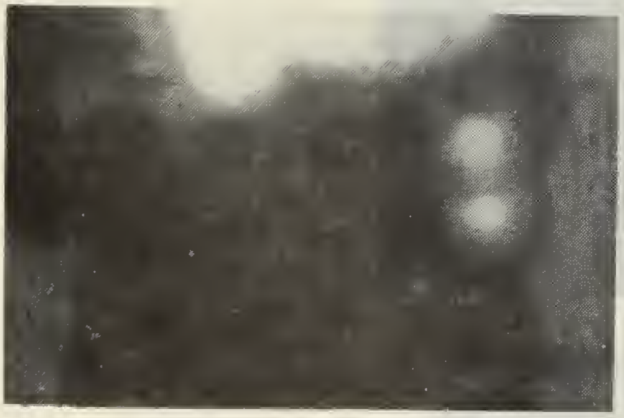
(b) time = to + 18.5 ms

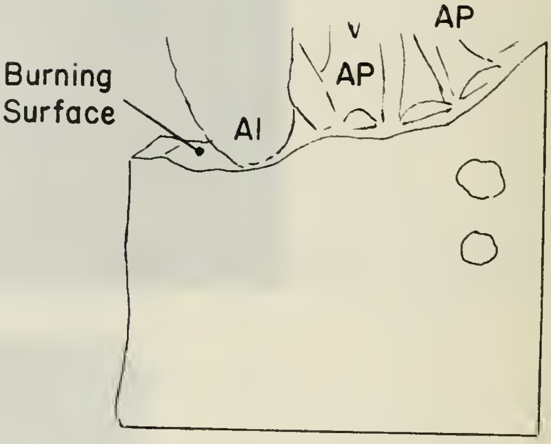
Figure 17. Time sequence of N-3 Propellant Combustion at 100 psig (.153 in. wide x .035 in. thick)



(a) Black and White Reproduction (b) Schematic: ⁄⁄⁄⁄ Red, ⋰ Blue

Figure 18. Schlieren of N-8 Propellant Combustion at 500 psig (.215 in. wide x .022 in. thick)





(a) Black and White Reproduction (b) Schematic

Figure 19. N-8 Propellant Combustion at 100 psig (.192 in. wide x .025 in. thick)

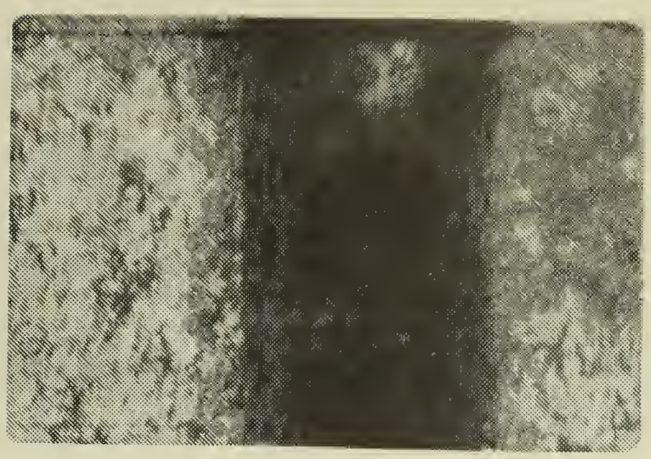


Figure 20. "Speckle" Background Effect

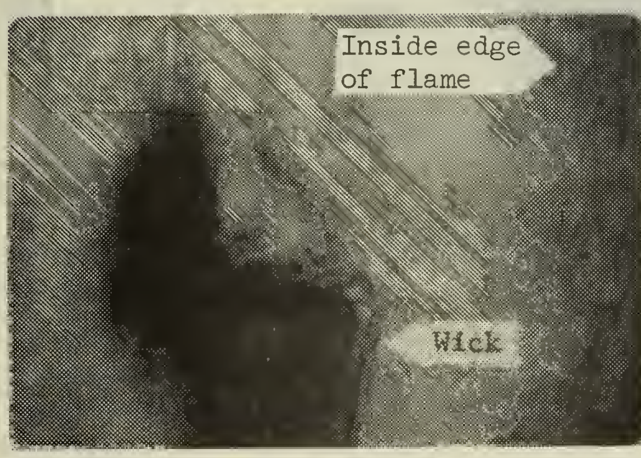
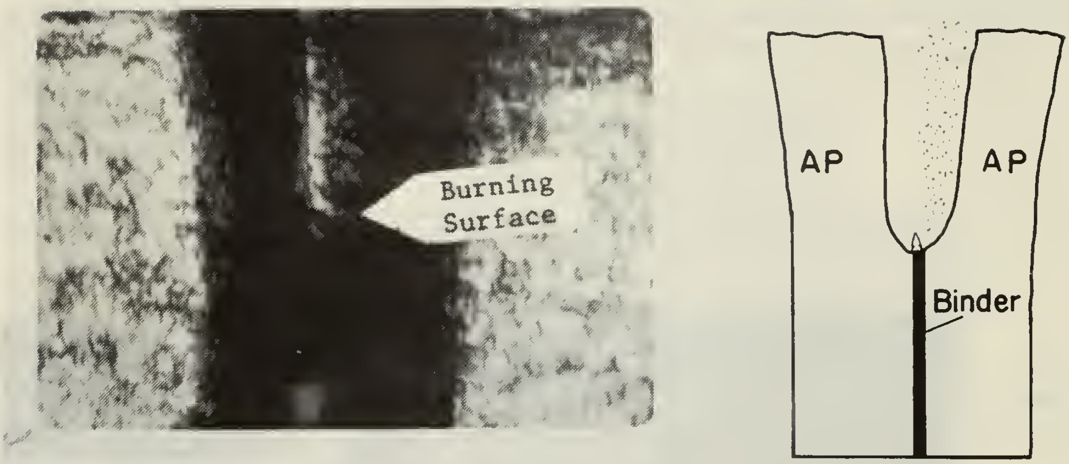


Figure 21. Laser Schlieren of Candle Flame



(a) Black and White Reproduction (b) Schematic

Figure 22. Laser Schlieren of AP/PBAA Sandwich Burning at 100 psig

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